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13. ABSTRACT (Maximum 200 words) Further investigation of radiative heating and boundary layer problem in electrothermal-chemical devices shows that radiative heating plays a major role in burn process at the plasma-propellant interface. However, combined effect of both radiative heating and plasma kinetic pressure is not totally resolved. Measured burn rates shows increased burn for increased plasma pressure, however, analysis of plasma parameters for same data revealed an increased burn rate for increased plasma temperature. Assessing the effect of plasma parameters on burn rates necessitates decoupling combined effects, especially the pressure and temperature. The measured pressure peaks to 3200 psi for a nozzle attachment that has a conical shape for choked flow. The radiation transport model has been tested without surface ablation, and is currently added to the most recent code version, to investigate the effects of radiation in cases with ablation. A new extrapolation boundary condition has been implemented at the surface. This boundary condition gives improved radiation energy profiles near the wall, and is consistent with the diffusion approximation used in the radiation transport model.			
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Progress Report

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AUGMENTATION AND CONTROL OF BURN RATE IN PLASMA-DEVICES

**(Contract N00014-95-1-1221, R&D Number 33e1016---01)
Department of the Navy, Office of Naval research**

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The growing interest in electrothermal-chemical propulsion necessitates better understanding of plasma-propellant interaction processes, and the role of plasmas in augmenting/enhancing the burn rates of propellants. Plasma parameters, e.g. temperature, pressure, density, velocity, etc. depend on the operational conditions of electrothermal sources used for this purpose. A plasma interacting with an energetic material mixes the plasma electrical energy with chemical energy from energetic material. Mixing processes are complex and governed by the initial micro-processes within the boundary layer at the plasma-propellant interface. Our approach focuses on:

- Boundary layer physics in electrothermal-chemical devices.
- Experiments and modeling of plasma flow.
- Vapor shield effect.
- Diagnostics development.
- Effect of plasma parameters on burn rates.

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During this reporting period, we report on the progress in the experiment and on the computational modeling. The experimental efforts are focused on radiative heating and decoupling

techniques for the effect of individual plasma parameters on burn rates. Theory and modeling focuses on radiation transport.

Radiative Heating and Decoupling Technique Experiments:

It has previously been shown that the vapor shield mechanism has a strong effect on radiative heating, and the energy transmission factor through the vapor shield is about 10%, which suggests that radiative heating may be limited during the burn of the propellant due to limited energy transport to the surface. Experiments have shown increased burn rate with increased plasma pressure when injection is normal to the surface of the propellant. Fig. 1 shows the burn rate as a function of plasma pressure at the surface. Due to the fact that the vapor shield may reduce the effectiveness of radiative transport to the surface, as has been shown by the energy transmission factor, one may conclude that the increase in burn rates is dominated by the plasma kinetic pressure. However, it is apparent that radiative heating plays a major role in enhanced burn rates. In order to investigate the temperature effect, one has to investigate the burn rate as a function of plasma temperature for the same set of data shown in Fig. 1. The code results for these shots predict the core plasma temperature, and results are displayed in Fig. 2. It is clear from Fig. 2 that the burn rate increases with increased plasma temperature, and matches the same increasing trend observed with increased pressure. This suggests that radiative heating is responsible for enhanced burn rates. However, the plasma density for these shots is also increasing with increased pressure, and a coupled pressure-temperature effect is still dominant.

In order to assess radiative heating versus pressure effect on burn rates, a set of decoupling experiments will be necessary. Decoupling experiments on PIPE Plasma-Propellant Facility necessitates the use of barrel section attachments to change either the pressure or the temperature for a given input energy to the plasma source. A straight nozzle attached to the source allows for extended plasma flow, at the same pressure, but reducing the plasma temperature via moderating material on the nozzle wall. Maintaining the plasma temperature and varying the pressure may be achieved via a conical nozzle geometry for choked flow at the source exit. Fig. 3 illustrates the choked flow nozzle attachment, where a conical nozzle is attached to the plasma source "capillary". The attachment is equipped with an absolute pressure transducer to measure the pressure at the nozzle exit.

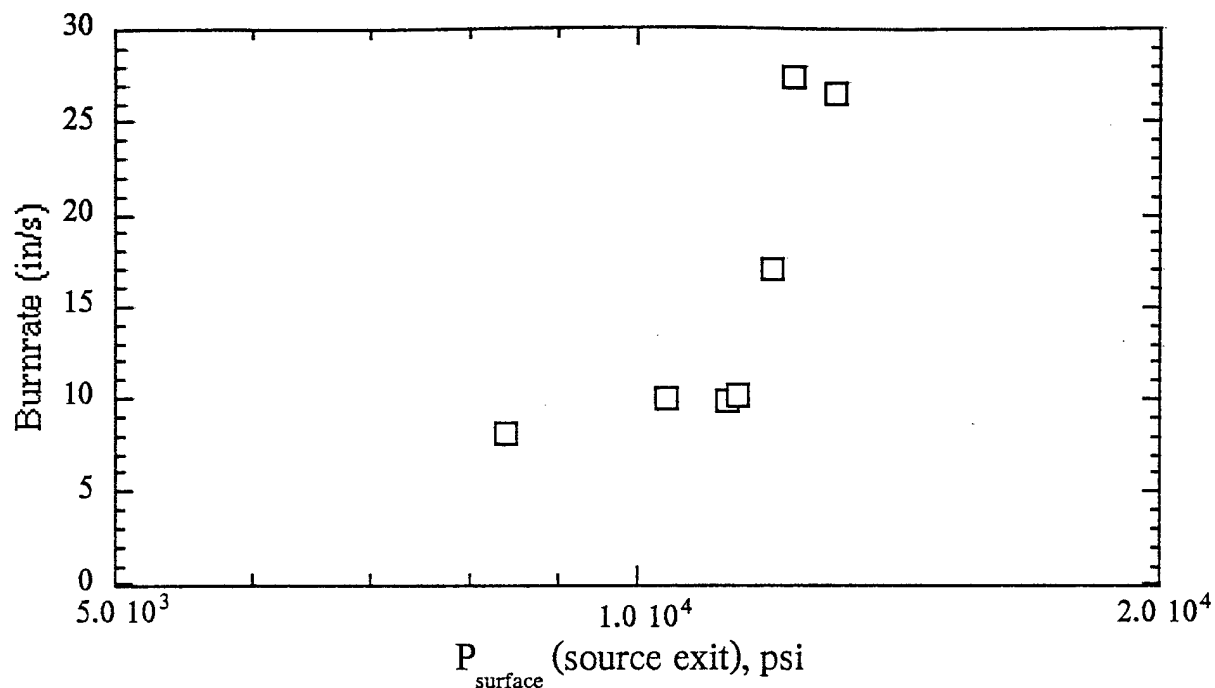


Fig. 1 Burn rate of JA-2 solid propellant as a function of plasma pressure at the surface of the propellant. Plasma is incident normal to the surface of the propellant.

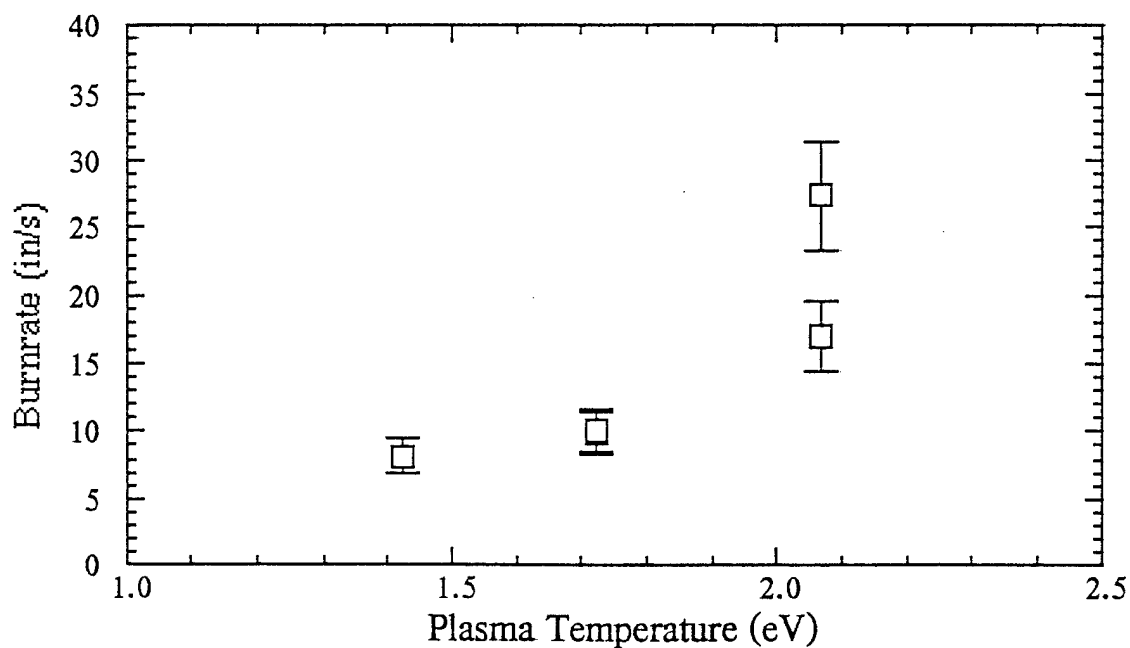


Fig. 2 Burn rate of JA-2 solid propellant as a function of plasma temperature. Burn rate is measured experimentally, and plasma temperature is calculated from SODIN code for same shots.

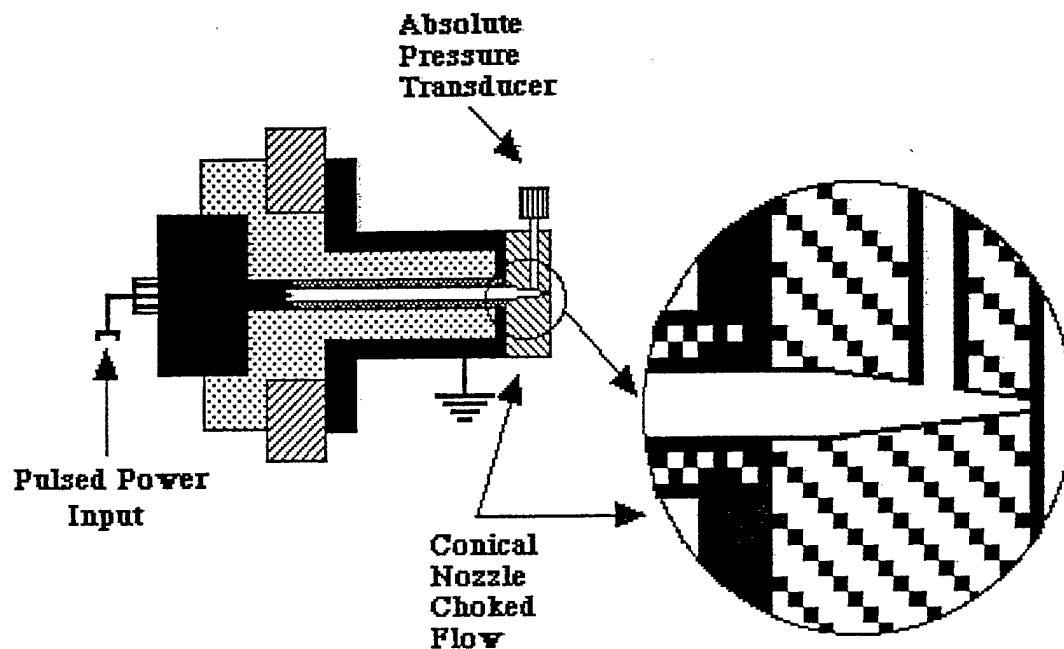


Fig. 3 Illustrative drawing showing choked flow conical nozzle attachment. Pressure transducer is situated close to the nozzle exit.

In order to test the attachments, two shots were conducted with a straight attachment without moderating material in the bore, and with the nozzle attachment that reduces the bore to half of its diameter. Each attachment has an absolute pressure transducer to measure the pressure at the source exit. Both shots were performed at same input energy to the source, providing 12-13 kA discharge current. The measured pressure peaks to 1000 psi for the straight attachment , and peaks to 3200 psi for the nozzle attachment. Fig. 4 shows the measured pressure for choked flow nozzle, where the pressure peaks to 3200 psi in 0.4 ms.

In order to assess the feasibility of using this technique for decoupling pressure-temperature effects, a series of shots will be conducted at various energy inputs to the source, where the pressure will be measured for each shot, and optical emission spectroscopy will be used to determine the plasma temperature and density.

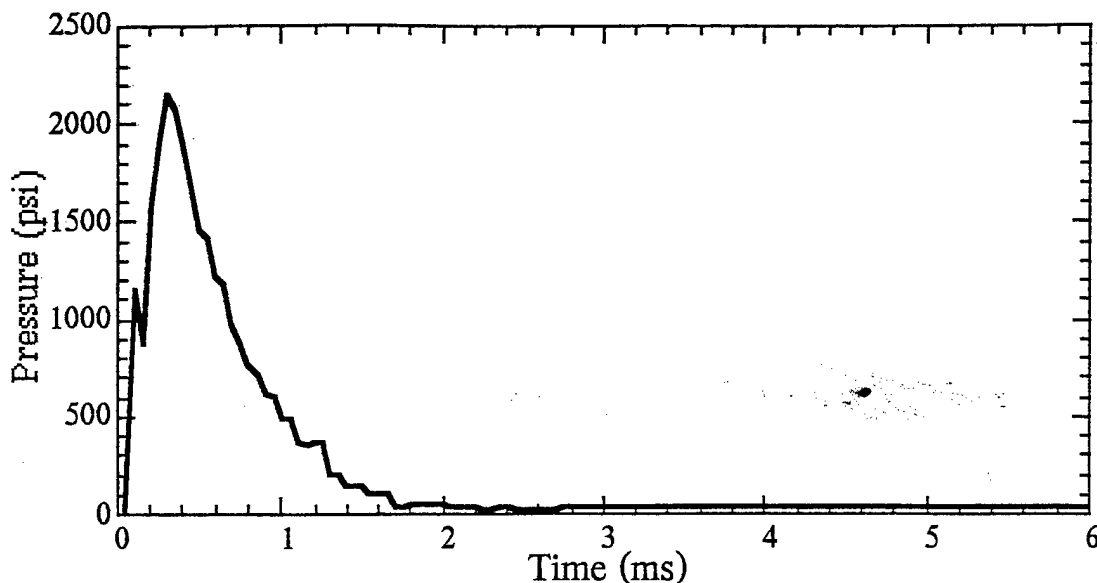


Fig. 4 Measured pressure for choked flow nozzle, for an input energy of 3 kJ to the plasma source. Pressure peaks to 3200 psi in 0.4 ms.

Theory and Code Development:

The radiation transport model has been tested without surface ablation. It is currently being added to the most recent code version, to investigate the effects of radiation in cases with ablation. A new extrapolation boundary condition has been implemented at the surface. This boundary condition gives improved radiation energy profiles near the wall, and is consistent with the diffusion approximation used in the radiation transport model. Fig. 5 shows the effects of turbulence and radiation on the boundary layer temperature profile, for free-stream plasma velocity of $u_{fs} = 1$ km/s, temperature $T_{fs} = 2$ eV, and wall temperature $T_{Wall} = 2000$ K. These code runs were conducted with a free stream density of about 1.5×10^{22} /cm³, with no surface ablation. The results show that turbulence increases the temperature by as much as 6000 K near the wall, and adding radiation increases the temperature by as much as 7000 K above this. Both turbulence and radiation cool the plasma further away from the wall, thereby increasing the boundary layer width.

Effects of Turbulence & Radiation on Temperature Profile

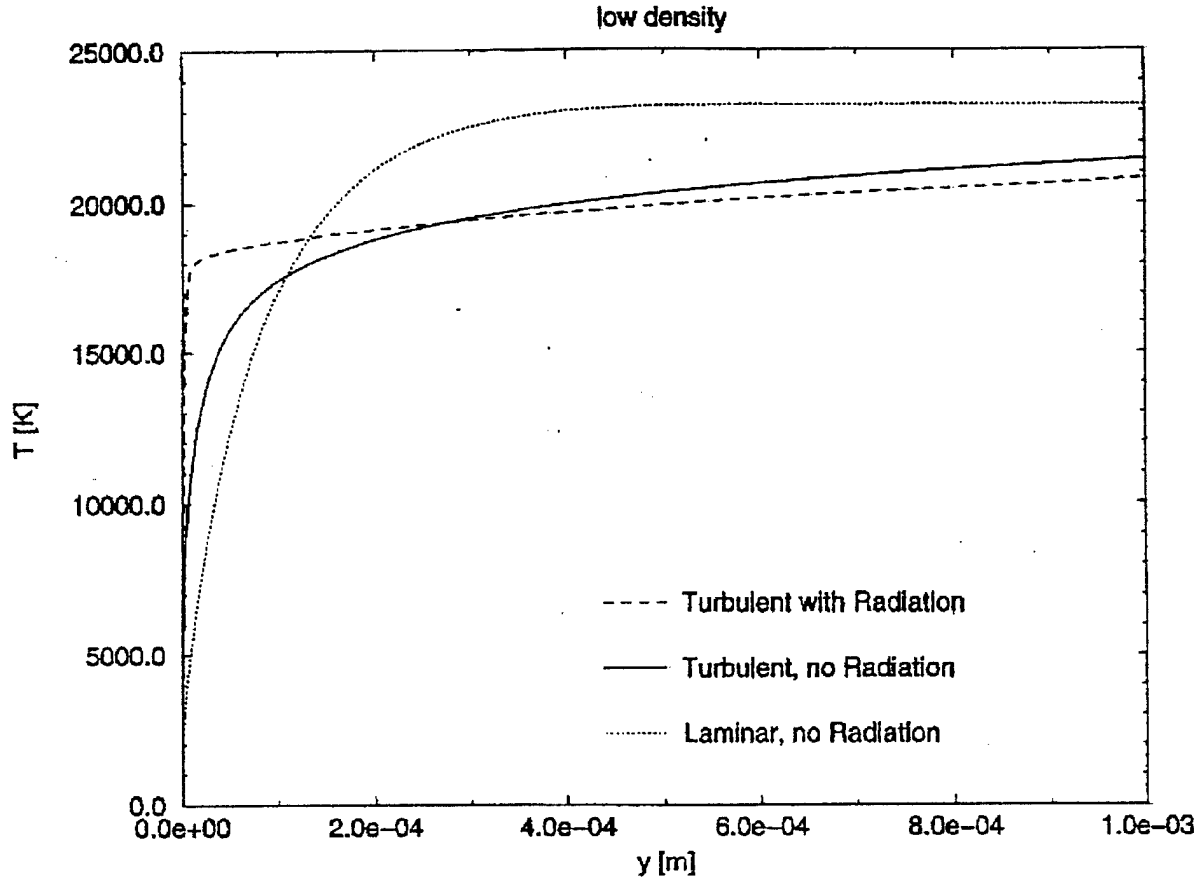


Fig. 5 Effects of turbulence and radiation on the temperature profile for $\rho_{fs} = 1.5 \times 10^{22}/\text{cm}^3$

With ablation, the density will be higher near the wall. It is expected that this will decrease the heating due to radiation because of the shorter radiation mean free paths (the vapor shielding effect). To investigate this, runs were conducted with a free stream density of $10^{24}/\text{cm}^3$. These runs were not intended to accurately model cases with surface ablation, since the density profile was not realistic. They should, however, provide insight into the effect of higher density on energy transport via radiation and turbulent convection. As expected, the effect of radiation was seen to be much smaller when density was increased, and the effect of turbulence was larger, as shown in Fig. 6. A more thorough investigation of the effects of radiation transport and turbulence will be conducted after the radiation transport and ablation models are combined.

Effects of Turbulence & Radiation on Temperature Profile

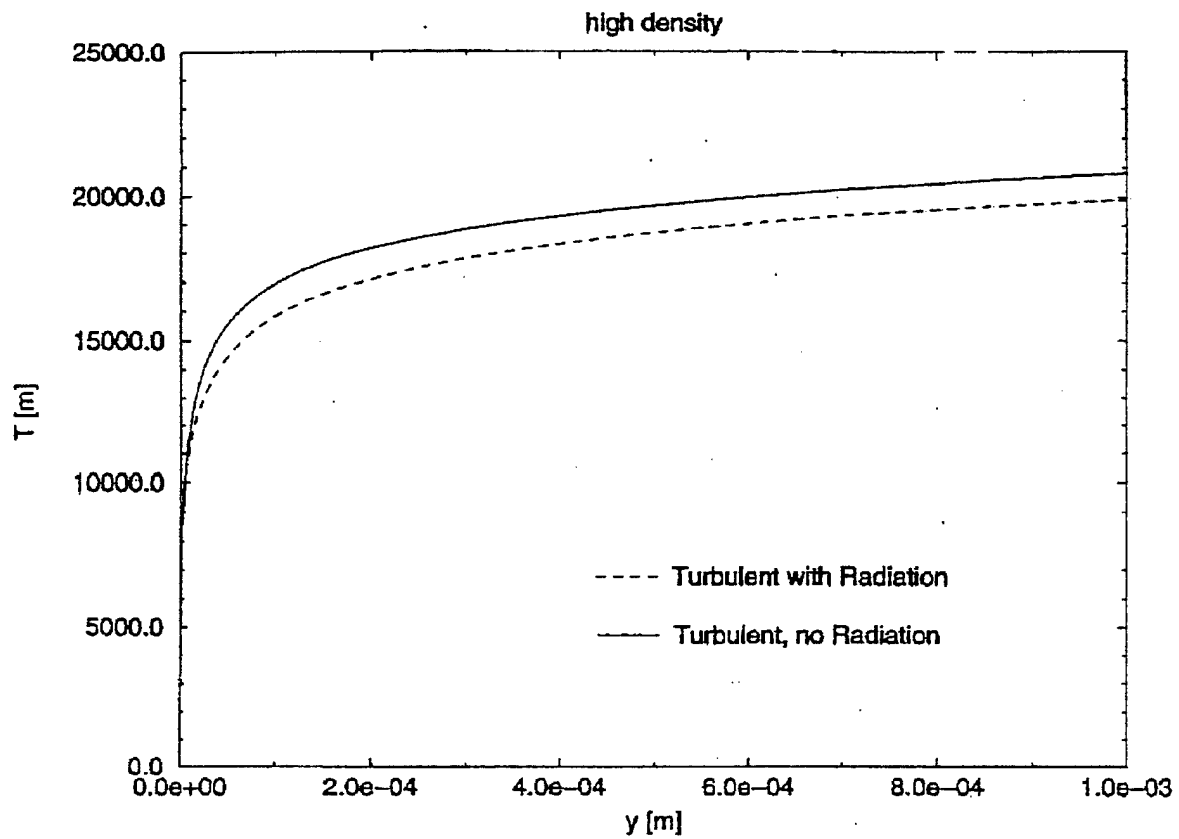


Fig. 6 Effects of turbulence and radiation on the temperature profile for $\rho_{fs} = 1.5 \times 10^{24}/\text{cm}^3$

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